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Antibacterial activity of amino- and amido- terminated poly (amidoamine)-G6 dendrimer on isolated bacteria from clinical specimens and standard strains

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Abstract

Background: Nanoscale poly (amidoamine) dendrimers have been investigated for their biological demands, but their antibacterial activity has not been widely discovered. Thus, the sixth generation of poly (amidoamine) dendrimer (PAMAM-G6) was synthesized and its antibacterial activities were evaluated on Gram-negative bacteria; *P. aeruginosa, E. coli, A. baumannii, S. typhimurium, S. dysenteriae, K. pneumoniae, P. mirabilis,* and Gram-positive bacteria, and *S.aureus and B. subtilis,* which were isolated from different clinical specimens and standard strains of these bacteria.

Methods: In this study, 980 specimens including urine (47%), blood (27%), sputum (13%), wounds (8%), and burns (5%) were collected from clinical specimens of 16 hospitals and clinics in city of Sabzevar, Iran. Then, the target bacteria were isolated and identified using standard methods. Minimum inhibitory concentration and minimum bactericidal concentrations against Gram-positive and Gram-negative bacteria were determined according to guidelines described by clinical and laboratory standards institute (CLSI). Standard discs were prepared using 0.025, 0.25, 2.5, and 25 µg/mL concentrations of PAMAM-G6 on Mueller-Hinton agar plates to determinate the zone of inhibition. The cytotoxicity of PAMAM-G6 dendrimer was evaluated in HCT116 cells by MTT assay.

Results: The most important isolated bacteria were *E. coli* (23.65%), *S. aureus* (24.7%), *P. aeruginosa* (10.49%), *B. subtilis (7.7%), S. typhimurium (8.87%), A. baumannii (7.02%), K. pneumoniae* (7.1%), *P. mirabilis* (6.46%), and *S. dysenteriae (3.6%)*. Moreover, it was found that poly (amidoamine)–G6 exhibited more antibacterial efficacy on standard strains than isolated bacteria from clinical samples ($p<0.05$). The cytotoxicity of PAMAM-G6 to the cells showed that cytotoxicity depended on the concentration level and exposure time.

Conclusion: The PAMAM-G6 dendrimer showed a positive impact on the removal of dominant bacterial isolated from clinical specimens and standard strains.

Keywords: Antimicrobial resistance, Cytotoxicity, Poly (amidoamine)-G6, Health care-associated infections, Nosocomial pathogens, Novel antibacterial, Synthesis

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Introduction

Health care-associated infections (HCAI) are a common cause of morbidity and mortality and are considered to be one of the most adverse events in health care. Also, these infections prolong hospitalization, require further extensive diagnostics and treatment, and are associated with additional costs (1). The failure of treatment for these in-

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↑What is "already known" in this topic:
Health care associated infection (HCAI) presents a major problem for patient safety and could lead to prolonged hospitalization, long-term disability, high costs for patients and their families, and excess deaths.

→What this article adds:
Amino-terminated PAMAM-G6 dendrimer is an effective antimicrobial agent against common Gram-negative and Gram-positive pathogens. Hence, PAMAM-G6 could be an excellent candidate for a new class of antimicrobial compounds and could be incorporated to combat dominant bacteria in health care centers.

fections is primarily due to the emergence of multidrug-resistant strains (MDR), which is a worldwide health care concern (2). Approximate ly 90% of HCAI are caused by bacteria (3). The most important MDRs associated with these infections are methicillin resistant *S. aureus* (4), extended-spectrum beta-lactamase-producing *E. coli* (5), *carbapenemase resistant A. buamanii* (2)*, and P. aeruginosa* (6). Therefore, considering the increasing prevalence of nosocomial infection by strains of MDR, the discovery and development of novel antibacterial agents, particularly those with structures and mechanisms of action different from traditional antibiotics, and a low potential to induce antibiotic resistance, now more than ever there is a need to control and treat health care- associated infections. Recently, the rapid growth in nanotechnology has spurred significant interest in the environmental applications of nanoparticles (NPs). NPs are excellent adsorbents, catalysts, and sensors due to their large specific surface area and high reactivity (7). More recently, several natural and engineered NPs including dendrimer NPs (8, 9), copper oxide (10), and zinc oxide (11) NPs have also been shown to have strong antimicrobial properties. However, dendrimers are a relatively new class of regularly branched macromolecules with unique structure and topological features that have emerged as strong antibacterial agents.

A typical dendrimer consists of a core molecule, monomeric branches called dendrons and surface functional groups that are able to react with other compounds (12). PAMAM dendrimers have been thoroughly explored for drug delivery and antimicrobial applications and have illustrated promising results, with amino-terminated dendrimers showing high antibacterial efficacy (13, 14). Their high antibacterial activity potential is attributed to the electrostatic interaction between the cationic dendrimer and the anionic bacteria cell surface with resultant disruption of the lipid bilayer, consequent cell lysis, and death. Thus, dendrimer biocides may be beneficial with respect to activity, localization in specific organs, reduced toxicity, and increased duration of action (13). An increase in the generation of PAMAM dendrimers is followed by a double increase in the number of functional amine groups in the structure of dendrimer (15). We designed a conceptional scheme of PAMAM-G6 dendrimer, which shows the number of functional amine groups in each generation (Fig. 1). Considering the fact that bacteria cause hospital infections and also considering the problem of MDR in bacteria, evaluating possible antibacterial properties in dendrimers and taking advantage of their ability as an antibacterial and antiseptic can be a research priority .The present study was conducted to determine the antibacterial properties of PAMAM-G6 dendrimer to remove the isolated bacteria from clinical specimens and standard strains bacteria. Overall, all the dominant bacteria related to HCAI have been investigated in the current study.

Methods

Sampling and target bacteria

In this study, sampling was performed in 16 hospitals and clinics in the city of Sabzevar, Iran, during August 2015 and May 2016. In total, 980 clinical samples including urine (47%), blood (27%), sputum (13%), wounds (8%), and burns (5%) were collected from hospitals and clinics. Then, the samples were transferred into medical microbiology laboratory. Several smears were prepared from each sample and Gram and Giemsa staining were done simultaneously. Urine Samples were cultured in Mac Conkey Agar, blood agar, and Eosin methylene blue agar (EMB). Blood cultures of tryptic soy broth (TSB), Castaneda medium, and lysis centrifuge method were used. Also, Mac Conkey Agar and blood agar were used for sputum culture, and wounds samples were cultured in blood agar and chocolate agar. After 24 hours of incubation at 37°C, differential catalase, oxidase, coagulase, indole, MRVP, TSI, SIM, citrate, and urease tests were per-

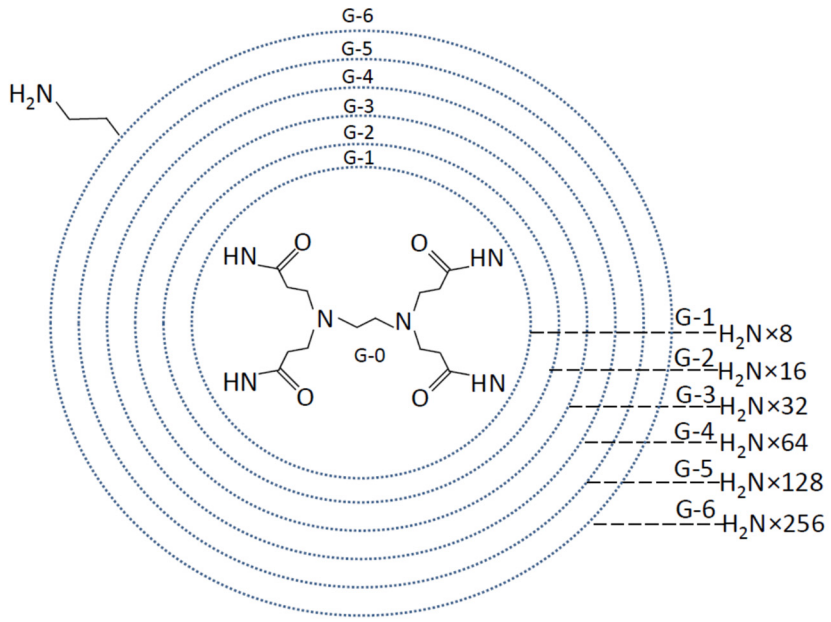

Fig. 1. Conception of PAMAM-G6 dendrimer

formed to identify the bacterial species. The isolated bacteria included Gram-negative bacteria; *P. aeruginosa, E. coli, A. baumannii, S. typhimurium, S. dysenteriae, K. pneumoniae, P. mirabilis, Gram-positive bacteria, and S. aureus and B. subtilis*. Standard strains used in this study were *E. coli* ATCC 25922, *P. aeruginosa* ATCC 27853, *A. baumannii* ATCC 17957, *S. typhimurium* ATCC 19430, *S. dysenteriae* ATCC 13313, *K. pneumoniae* ATCC 1705, *P. mirabilis* ATCC 29906, *S. aureus* ATCC 25923, and *B. subtilis* ATCC 23857, which were provided by Iranian Research Organization for Science and Technology (IROST) and Pasteur Institute of Iran. Before use, all bacteria were cultured on specific media.

Synthesis and properties of antimicrobial agent

Tomalia's divergent growth approach is the most common method to synthesize ethylenediamine core PAMAM dendrimers (16). PAMAM-G6 was synthesized following a 2-step process, involving Michael addition of a suitable amine initiator core with methyl acrylate (MA), and exhaustive amidation of the resulting esters with large excess of ethylenediamine (EDA), reported elsewhere (17). Briefly, ethylenediamine (10.0 g, 0.166mol) was dissolved in 100 mL methanol in a 1-l round-bottomed flask. Methyl acrylate (94.6 g, 0.751mol) was added at 40 ^{0}C and stirred for 24 hours in the presence of nitrogen exposure. Excess methyl acrylate was removed under vacuum condition at room temperature. A Michael addition between the amine and the acrylate yielded a product bearing 4 terminal methyl ester groups, defined as the G0.5 PAMAM. Subsequently, ethylenediamine (120 g, 2.00 mol) was dissolved in methanol and added to the G0.5 PAMAM. Then, a product bearing 4 terminal amino groups was obtained and defined as the G1 PAMAM after stirring for 48 hours in the presence of nitrogen. Moreover, by removing excess reactants using vacuum distillation, seventh generation PAMAM dendrimers was synthesized through repeating the above cycle. The chemical formula of PAMAM-G6 is $C_{2542}H_{5088}N_{1018}O_{508}$, molecular weight equal to 60713 g/mol, and the number of terminal amine groups is 256. Fourier transform infrared (FTIR, TENSOR 27 FTIR spectrometer, Bruker, Germany) was used to clarify the structural behavior of dendrimer on the molecular level. The samples were mixed with potassium bromide (KBr) powder, and then the mixtures were made into pellet under high pressure. The sample pellet was scanned from 400 to 4000 cm^{-1}. Pure KBr acted as blank. Morphology and size distribution of PAMAM-G6 was analyzed using transmission electron microscopy (TEM, Philips CM 30). For the TEM investigations, the samples were dispersed in ethanol and deposited by placing 2 drops of NPs suspension onto carbon-covered copper-grids, followed by drying at room temperature.

Antimicrobial susceptibility testing

Serial dilution of antimicrobial agent was prepared with using sterile distilled water to assess the antimicrobial activity of dendrimer. Clinical and Laboratory Standards Institute (CLSI) determined the antimicrobial activity of dendrimer by calculating minimum inhibitory concentration (MIC) and minimum bactericidal concentrations (MBC) using the serial dilution method (18). Also, disc diffusion method was used to determinate the zone of inhibition.

Disc diffusion method

A bacteria culture that has been adjusted to 0.5 McFarland standard was evenly applied to Mueller-Hinton agar (MHA) plates using a sterile swab. The volume of 25 µL of antibacterial agent in different concentrations (0.025, 0.25, 2.5 and 25 µg/mL) was impregnated to standard blank disc (6 mm in diameter). The discs were dried for 30 minutes and placed on the MHA seeded with the target culture and were incubated at 37°C for 24 hours.

Experiments of MIC and MBC

To determine the exact amount of MIC and MBC of bacteria, experiments with different concentrations (0.025, 0.25, 2.5, 25, 50, 100 and 200µg/ml) of antimicrobial agent were conducted. Tubes containing 10 mL of nutrient broth (consisting of 10^8CFU/mL of bacteria and different concentrations of dendrimer) incubated in optimal conditions.

The positive control contained bacteria, with no dendrimers. Also, the negative control contained dendrimers in the absence of bacteria. A tube with the lowest concentration of antimicrobial agent and no bacterial growth was reported as MIC. To determine MBC, a loop of each tube with no growth transferred to nutrient agar plates and incubated in optimal conditions. A plate with no bacterial growth was taken as the MBC value.

Cell cytotoxicity detection by MTT assay

Cytotoxicity assessment was performed by MTT assay in HCT116cells (19) (human intestinal cancer cell line), which was purchased from the Pasteur Institute Cell Bank of Iran (http://ncbi.pasteur.ac.ir/). Briefly, 5000 cells suspended in 96-well plates diluted in 100 µL RPMI 1640 media (Invitrogen, Carlsbad, CA) were supplemented with10% heat-inactivated fetal bovine serum (FBS, Invitrogen, Carlsbad, CA), and 100 mg/mL penicillin-streptomycin (Invitrogen, Carlsbad, CA) at 37 °C in a humidified atmosphere containing 5 % CO_2. After 24 hours that all cells were attached to the baseline, 100 µL of medium containing different concentration of PAMAM-G6 (5, 10, 20, 40, 60, 80 and 100 µg/mL) were added to each determined well and incubated in above conditions for 48 and 72 hours. One of the seeded wells in each repeat was used as a control in the absence of PAMAM-G6 dendrimer. After incubation, 20 µL containing 5 mg/mL MTT were added to the wells and incubated again for 4 hours. During this time, the MTT (yellow tetrazolium salt) was enzymatically converted into the purple formazan precipitate by viable cells, and the concentration of formazan showed the proportion of viable cells. Subsequently, all media were aspirated from the cells, then, 150 µL of DMSO was added to dissolve the formazan. Finally, absorbance was detected at 490 nm wavelength by ELISA plate reader.

Data analysis

Statistical analysis was performed using Mann-Whitney U test analysis. Statistical significance was set at $p<0.05$. Every experiment was repeated at least 3 times.

Results

As demonstrated in Fig. 2, the isolated bacteria were *E. coli* (23.65%), *S. aureus* (24.7%), *P. aeruginosa* (10.9%), *B. subtilis (7.7%), S. typhimurium (8.87%), A. baumannii (7.02%), K. pneumoniae* (7.1%), *P. mirabilis* (6.46%), and *S. dysenteriae* (3.6%). Fig. 2 displays that the frequently of the isolated bacteria with the highest percentage (46.4%) were *E. coli*, *S. aureus,* and *P. aeruginosa* from urine and blood samples. In addition, these 3 bacteria were present in most urine, blood, sputum, wounds, and burns samples. In other words, 59.25% of all isolated species belong to these 3 bacteria. FTIR analysis of PAMAM-G6 NPs was performed to confirm the existence of characteristic amides, terminal amino, and etc. (Fig. 3). Results in Table 1 demonstrate the corresponding functional groups of the wavelengths, which are indicated in Fig. 3. The morphology and diameter of PAMAM-G6 NPs were studied by TEM as shown in Fig. 4. PAMAM-G6 NPs were shown to have a spherical shape with a mean diameter size of 20 nm. The results of different concentration of PAMAM-G6 dendrimer effect on isolated bacteria and standard strain (using disk diffusion method) are presented in Tables 2 and 3, respectively. According to the obtained results, PAMAM-G6 dendrimer actively inhibited the growth of isolated Gram- negative and Gram- positive bacteria and standard strains. However, the antibacterial activity of PAMAM-G6 on the isolated bacteria was less than that on the standard strains, whose difference was statistically significant ($p<0.05$). The most sensitivity was related to *P. mirabilis* ATCC 29906*, S. typhimurium* ATCC 19430*, S. dysenteriae* ATCC 13313, *and S. aureus* ATCC 25923 at the concentration of 25 (µg/mL) PAMAM-G6 with the inhibition zone of 35, 32, 31, and 30 mm, respectively. In addition, the least sensitivity was

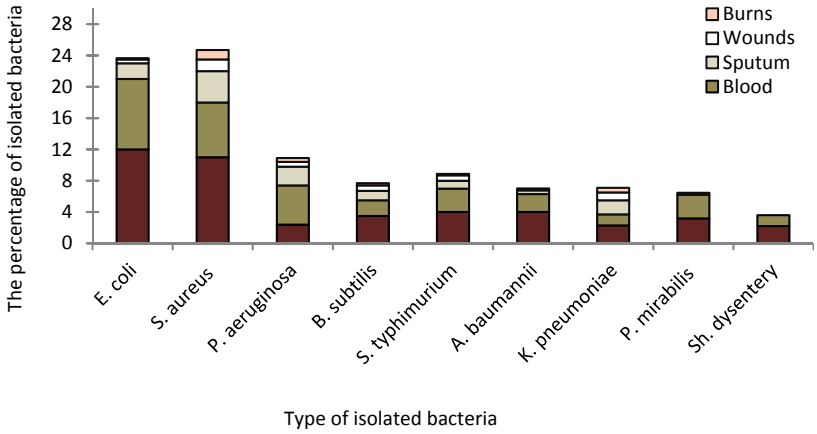

Fig. 2. Type of Isolated Bacteria and the Frequency Distribution of Each Bacterium in Urine, Blood, Sputum, Wounds and Burns Samples

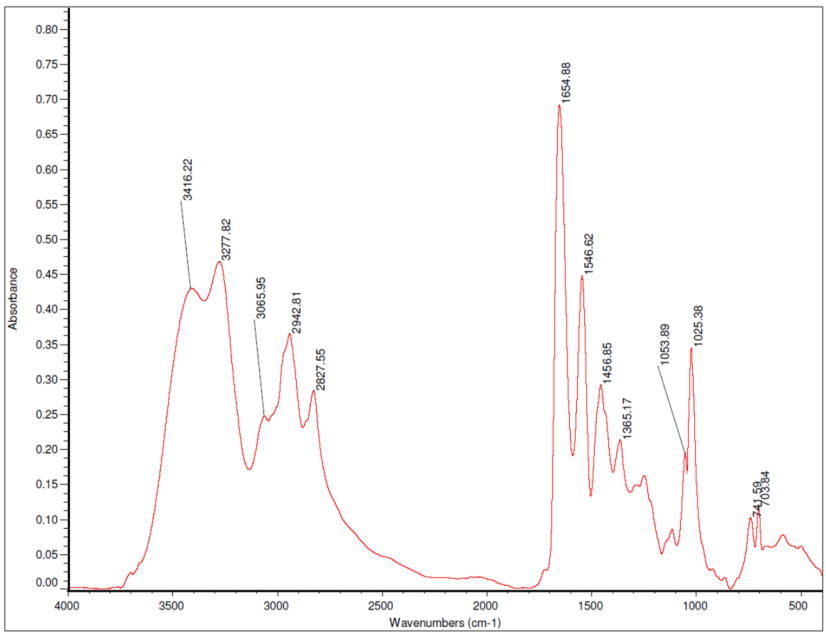

Fig. 3. FTIR Spectra of PAMAM-G6

Table 1. Band position of PAMAM-G6 spectrum

Wavenumber(cm^{-1})	Spectral assignments
1025.38	C–O stretching vibration
1654.88	C=O stretching (amide I)
1546.62	N-H bending/C-N stretching (amide II)
1456.85	H-C-H scissor
1365.17	H-C-H asymmetric
2827.55and 2942.81	C-H stretching vibrations
3416.22$cm^{-1}$and 3277.82	N-H stretching mode of amineI and amide groups

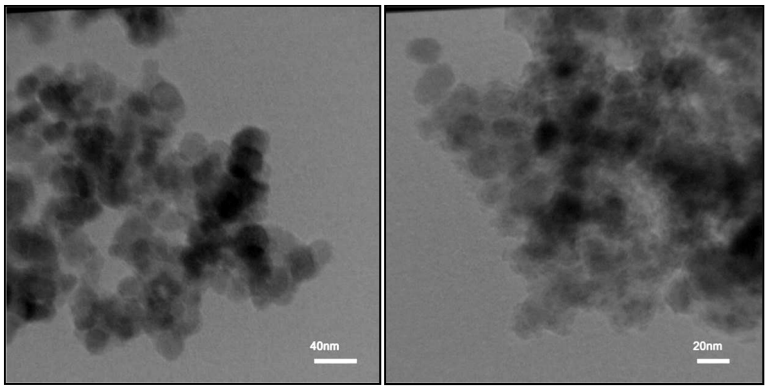

Fig .4. TEM Image of the PAMAM-G6

related to *A. baumannii* at 25 (µg/mL) concentration of dendrimer, with 10 mm zone of inhibition. The concentration of 0.025 (µg/ml) dendrimer had no effect on the studied bacteria, except *S. typhimurium, P. mirabilis, and S. aureus*. Comparison between MIC and MBC values of PAMAM-G6 for isolated bacteria and standard strains are presented in Tables 4 and 5, respectively. As can be seen in the tables, the maximum amount of MIC and MBC were related to isolated bacteria, ie, *E. coli and A. baumannii* at 25 and 200 µg/mL concentrations of dendrimer, respectively. Also, the minimum amount of MIC and MBC were related to *S. typhimurium* ATCC 19430 at 0.025 and 25 µg/mL concentrations, respectively. The effect of PAMAM-G6 on cell viability was assessed using MTT assay. This assay measured optical density of different concentrations in comparison with the rate of viable cells. As displayed in Fig. 5, there were little cytotoxicity effects of PAMAM-G6 with different concentrations in HCT 116 cells during 48 hours when no IC50 value was obtained (Graph pad prism 6, USA). The cytotoxicity effects after 72 hours (Fig. 5) were more than 48 hours, with no measurable IC50. However, high concentration in 72 hours had more effects compared to the same concentration in 48 hours.

Table 2. The Mean Diameter of Inhibition Zone of isolated bacteria VS Different PAMAM-G6 Dendrimer Concentrations

Dendrimer concentration, µg/ml	Zone of inhibition, mm								
	E. coli	*S.typhimurim*	*A.baumannii*	*K.pneumoniae*	*S.dysenteriae*	*P.aeruginosa*	*P. mirabilis*	*B. subtilis*	*S. aureus*
0.025	0	10	0	0	0	0	9	0	9
0.25	0	19	0	13	0	0	19	9	10
2.5	0	21	0	16	13	0	21	9	11
25	20	31	10	26	27	22	32	17	21

Table 3. The Mean Diameter of Inhibition Zone Of Standard Strain Bacteria VS Different Concentrations of PAMAM-G6 Dendrimer

Dendrimer concentration, µg/ml	Zone of inhibition, mm								
	E. coli ATCC 25922	*S.typhimuriumATCC 19430*	*A.baumanniiATCC 17957*	*K.pneumoniae ATCC 49131*	*S. dysenteriae ATCC 13313*	*P.aeruginosa ATCC27853*	*P. mirabilis ATCC 29906*	*B. subtilis ATCC 23857*	*S. aureus ATCC 25923*
0.025	0	14	0	0	0	0	11	0	11
0.25	0	22	9	19	14	0	21	9	11
2.5	9	23	13	21	18	9	22	9	17
25	24	32	20	27	30	22	35	21	30

Table 4. MIC and MBC of the PAMAM-G6 Dendrimer for Isolated Bacteria

Dendrimer concentration, µg/ml	Type of Effect								
	E. coli	*S.typhimurium*	*A.baumannii*	*K.pneumoniae*	*S. dysenteriae*	*P.aeruginosa*	*P. mirabilis*	*B. subtilis*	*S. aureus*
0.025	Growth	Growth	Growth	Growth	Growth	Growth	Growth	Growth	Growth
0.25	Growth	MIC	Growth	MIC	MIC	Growth	MIC	MIC	MIC
2.5	Growth	B.S	Growth	B.S	B.S	MIC	B.S	B.S	B.S
25	MIC	MBC	MIC	B.S	B.S	B.S	B.S	B.S	B.S
50	B.S	B.C**	B.S	B.S	MBC	B.S	B.S	MBC	B.S
100	B.S	B.C	B.S	MBC	B.C	MBC	MBC	B.C	MBC
200	MBC	B.C	MBC	B.C	B.C	B.C	B.C	B.C	B.C

B.S*: Bacteriostatic, B.C**: Bactericide

Table 5. MIC and MBC of the PAMAM-G6 Dendrimer for Standard Strain Bacteria

Dendrimer concentration, µg/ml	Type of Effect								
	E. coli ATCC 25922	*S.typhimuriumATCC 19430*	*A.baumanniiATCC 17957*	*K.pneumoniae ATCC 49131*	*S.dysenteriaeATCC 13313*	*P.aeruginosa ATCC27853*	*P. mirabilis ATCC 29906*	*B. subtilis ATCC 23857*	*S. aureus ATCC 25923*
0.025	Growth	MIC	Growth	Growth	Growth	Growth	Growth	Growth	Growth
0.25	Growth	B.S	Growth	MIC	MIC	Growth	MIC	MIC	MIC
2.5	MIC	MBC	MIC	B.S	B.S	MIC	B.S	B.S	B.S
25	B.S	B.C	B.S	B.S	B.S	B.S	B.S	B.S	B.S
50	B.S	B.C	B.S	B.S	MBC	B.S	B.S	MBC	B.S
100	MBC	B.C	B.S	MBC	B.C	MBC	MBC	B.C	MBC
200	B.C	B.C	MBC	B.C	B.C	B.C	B.C	B.C	B.C

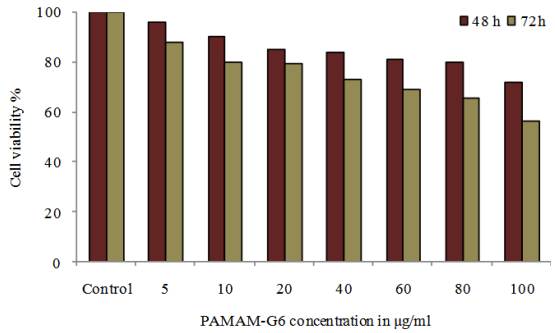

Fig. 5. Cytotoxicity of PAMAM-G6 in HCT116 Cells. Cell viability was determined by MTT assay in HCT116 cells in 48 h and 72 h. As depicted in this figure there are cytotoxicity effects in different concentration of PAMAM-G6 dendrimer during 48h and 72 h which it is high level in 72 h. The IC50 was not determined in both times. The reported values were carried out two independent experiments with 3 repeated times and untreated cells were assumed to be viable as control cells.

Discussion

A well-known problem in modern-day hospitalization is the occurrence of nosocomial or health care acquired infections caused by multi-resistant pathogens (3). PAMAM dendrimers have been investigated for their biological applications, but antibacterial activity has not been extensively explored (20). The 980 samples were tested. Fig. 2 shows the isolated bacteria with the highest frequency belonging to *E. coli* (23.65%), *S. aureus* (24.7%), and *P. aeruginosa* (10.9%). These 3 bacteria were mostly isolated from urine and blood samples as 46.4% of these bacteria were isolated from these samples; and of these 9 isolated strains, the highest frequency belonged to these 3 bacteria (59.25%). Similar results were observed by Salamati et al. (21), as they reported that the most common pathogenic organisms were *Enterobacter* (27%), *S. aureus* (21%), and *E.coli* (14%). Other studies also reported that the most common nosocomial infections were associated with *E.coli* (22), *P. aeruginosa,* and *S. aureus* (23). In a study conducted by Mazloomi et al. (24), on 172 specimens collected at a children medical center, the most frequent isolated bacteria were *S. aureus and P. aeruginosa.*

Ferreira et al. (25) investigated patients' urine and blood specimens and observed that the highest frequency of bacteria in urine and blood specimen belonged to *E. coli* and *S. aureus,* respectively. These pathogens, especially *E. coli, P. aeruginosa, S. aureus*, *A. baumannii, and K.* pneumoniae, are often HCAIs such as Bacteremia, UTIs,

pneumonia, and etc. (26).The size of the inhibition zone clearly shows that with increasing concentration of the antimicrobial agent, the zone surrounding the disks is expanded, which indicates the power of antimicrobial agent at higher concentrations. According to our findings, PAMAM derivatives could be considered as an excellent candidate for a new class of antimicrobial compounds that could be incorporated to combat health care-acquired infections. According to minimum bacteriostatic or bactericide levels (Tables 4 and 5), it is clear that PAMAM-G6 has antimicrobial effects and can be used as an antimicrobial agent. Previous studies have shown that antimicrobial agents cause bacterial cell membrane damage, spatial deformation, degradation of bacterial enzymes, and damage of chromosome and bacteria cell wall damage. This character refers to end amine groups in dendrimer structure, which interact with the negative charge of the membrane or cytoplasm microorganism, causing bacterial cell wall damage, and finally, inactivation of bacteria (27). In FTIR spectrum of PAMAM-G6 dendrimer (Fig. 3), 9 main peaks are detectable at 1025 cm^{-1}, 1365cm^{-1}, 1456 cm^{-1}, 1546cm^{-1}, 1654cm^{-1}, 2827cm^{-1}, 2942cm^{-1}3277cm^{-1}, and 3416cm^{-1} , with the last peak being related to N-H stretching vibration of primary amine. Other main band positions, based on wave number and their assignments are presented in Table 1. Overall, PAMAM-G6 dendrimer is an efficient antibacterial agent against both Gram-negative and Gram-positive bacteria. Our results are also consistent with those of Lopez et al. (28) study. They found that the antimicrobial effect of PAMAM dendrimers was modified with amine groups on Gram-positive and Gram-negative bacteria. Likewise, Xue et al. and Charles et al. found that amino-terminated PAMAM G2 and G3 dendrimers possess significant antibacterial effects against multi-resistant strains (12, 29). As shown in Tables 2 to 5, *E. coli, P. aeruginosa, and A. baumannii* had a higher resistance than other studied bacteria. Intrinsic and acquired resistance of these bacteria against the antibacterial agent can be attributed to the possible effect of lower concentrations of dendrimer PAMAM-G6 on the bacteria such as *E. coli, P. aeruginosa* (30), and *A. baumannii* (31) than other target bacteria. Mihani. et al. indicated that *P. aeruginosa* were resistant against ciprofloxacin (67%), ceftazidime (71%), and imipenem (41%) (32). Mohammadimehr et al. (33), also, showed that *E. coli* has a high resistance against ampicillin, amikacin and piperacillin inoculated discs. The findings of the present study are consistent with their results. The antibacterial activity of PAMAM-G6 on the isolated bacteria was less than that on the standard strains (Tables 2-5). For example, according to Table 4 and 5, the MIC of PAMAM-G6 related to *E. coli and A. baumannii* was 25µg/mL and the MIC of PAMAM-G6 was related *to E. coli* ATCC 25922, and *A. baumannii* ATCC 17957 was 2.5µg/mL. High resistance of bacteria isolated from hospital than standard strains can be attributed to the acquired resistance. Many studies also confirm that most bacteria in hospitals have been resistant towards most anti-bacterial materials. According to reports, most of *A. baumannii* isolated from clinical specimens were resistant to ciprofloxacin positions in the top 85% (34). A study conducted to evaluate the resistance of *P. aeruginosa* towards ceftazidime showed that in Lithuania 78.9% (35) has developed resistance to ceftazidime. The diameter of inhibition zone for *S. typhimurium*, *P. mirabilis,* and *S. aureus* was also observed at the concentration of 0.025 µg/mL of dendrimer PAMAM-G6 (Tables 3-4). The study conducted by Izanlo et al. (36) on the effect of PAMAM-G4 dendrimer on *E. coli*, *Enterobacter cloacae*, *B. subtilis* and *S. aureus* by means of disc diffusion method concluded that concentration of 0.05 µg/mL has no effect on these bacteria and also they found that the antibacterial effect of PAMAM-G4 occurs at higher concentrations. Izanlo et al. (37) examined the effect of dendrimer PAMAM-G4 on Klebsiella oxytoca, *P. mirabilis,* and *P. aeruginosa* using disc diffusion method and found that concentrations of 0.5, 5, and 50 µg/mL of PAMAM-G4 have no effect on these selected bacteria. Perhaps, the higher antibacterial effect of dendrimerPAMAM-G6, compared with lower generation dendrimers, can be attributed to high density, ordered and hyperbranching structure, high spatial void between branches, large number of terminal functional groups, and relatively large molecular size of PAMAM-G6 (20).These characteristics lead to highly specific area in dendrimer PAMAM-G6, which causes higher activity of dendrimers in the surface of culture and higher efficiency at lower concentrations. However, most importantly, it is the number of terminal amine groups of dendrimer for generation 4 is 64, while the number of terminal amine groups for PAMAM-G6 is 256 (38). These functional groups are adsorbed on the bacterial cell surfaces, diffused through the cell wall, and bonded to cytoplasmic membrane; and as a result, release electrolytes such as potassium ions and phosphate from the cell and also nucleic materials such as DNA and RNA due to disruption and disintegrate of the cytoplasmic membrane. Therefore, it is proposed that the antibacterial property of dendrimers be mediated by disrupting the bacterial outer and inner membrane by terminal amine groups (27). We also measured the cytotoxicity of PAMAM-G6 on the HCT 116 cell line, and the data revealed that the cytotoxicity will be increased in cells at higher concentrations and in long-term treatments. Mukherjee et al. studied cytotoxicity in different generations of PAMAM dendrimers with variety of doses. They found that increasing the dose of these dendrimers cause a decrease in the percentage of healthy and early apoptotic cells. They also demonstrated that the systematic mechanism in mammalian cells leads to cytotoxicity in various exposures of different generations of dendrimers. In line with a recent study, our data revealed a reduction in cell viability although the dose and exposure time are 2 important factors. This result is consistent with a study that found PAMAM could lead to the formation of nanoscale holes in eukaryotic membranes at high concentrations (39). Increasing the number of surface amino groups in the dendrimers and zeta potential may give rise to toxicity after increasing generation and diameter (19).

Conclusion

This study evaluated the antibacterial effects of PAMAM-G6 on the isolated bacteria from clinical specimens

and standard strains using MIC, MBC, and disc diffusion method. The highest number of isolated bacteria was related to *E. coli* (23.65%), *S. aureus* (28.7%), and *P. aeruginosa* (10.9%). In this study, we found that amino-terminated PAMAM-G6 dendrimer is an effective antimicrobial agent against common Gram-negative and Gram-positive pathogens. Bacteria origination is one of the important variables affecting the performance of PAMAM-G6. The antibacterial activity of PAMAM-G6 on the isolated bacteria was less than that on the standard strains. Although increasing the concentration of PAMAM-G6 improves removal efficiency, their cytotoxicity in mammalian cells has to be considered at higher concentrations. However, the low levels have relatively high antibacterial effects on Gram- negative and Gram- positive bacteria. *A. baumannii* has the least sensitivity to PAMAM-G6, where *P. mirabilis* ATCC 29906, *S. typhimurium* ATCC 19430, *S. dysenteriae* ATCC 13313, *and S. aureus* ATCC 25923 have the highest sensitivity. These findings indicated that PAMAM-G6 could be an excellent candidate for a new class of antimicrobial compounds and could be incorporated to combat dominant bacteria in health care centers.

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Conflict of Interests

The authors declare that they have no competing interests.

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